Qualitative behavior of LHM and related meta-materials

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We investigate the transmission properties of one-dimensional LHM and related meta-materials of the split-ring resonator (SRR) and continuous wire type, both theoretically and experimentally. Theoretically, we use a fast implementation of the transfer matrix method, which allows us to directly simulate the complex transmission and reflection amplitudes for arbitrary structures inside the unit cell, even for long systems. Moreover, under the assumption that the meta-material behaves like an effective medium, we apply an inversion procedure to the obtained scattering data, to retrieve the effective permittivity and permeability as a function of frequency. This allows us to show the negative index of refraction $n(\omega) < 0$ together with simultaneously $\varepsilon_{\rm eff}(\omega) < 0$ and $\mu_{\rm eff}(\omega) < 0$inside the left-handed bandpass for the one-dimensional materials and normal incidence.

We show that the explanation for the LHM behavior is more complicated than just the combination of the negative $\mu_{\rm eff}(\omega)$ provided by the SRRs with the negative $\varepsilon_{\rm eff}(\omega)$ from the wires, and *we propose a simple analytic model for this behavior*. Our model allows the qualitative interpretation of the complete low frequency spectrum (up to roughly three times the magnetic resonance frequency) of a meta-material. It also explains the occasional appearance of right-handed instead of the expected left-handed bandpasses in LHM around the SRR resonance. The models validity is confirmed by a variety of associated experimental measurements, concerning meta-material structures and their various components and variants.